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An Introduction to the Physiography and History of the Bisley Experimental Watersheds in the Luquillo Mountains of Puerto Rico

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SUMMARY

This paper summarizes the physiographic setting and historical uses of the Bisley experimental watersheds. These watersheds are the site of long-term watershed studies in the Luquillo Experimental Forest of Puerto Rico. Each of these watersheds drains deep, clayey soils that overlie a highly dissected terrain underlain by volcanoclastic sandstones. The drainages are covered by secondary tabonuco type forests and receive about 3,500 mm/yr of rainfall.

Since European settlement, about 490 years ago, the study area has been explored for precious ores, cultivated, and selectively logged. The major obstacle to the exploitation of the resources of the watersheds has been inaccessibility. High rainfall, steeply sloping terrain, and slippery clay soils combine to make transportation in the area difficult.

The most rapid change to the Bisley landscape occurred at the end of the 19th century and the beginning of the 20th century. During this time, local agricultural activity was at a maximum, timber was being exported from the region, and copper mines were active in the Rio Blanco area. In addition to human activity, major hurricanes occurred in 1892 and 1932.

Human-induced disturbance in the watersheds has been selective in both space and time. The pattern of disturbance is contrary to that described in other temperate and tropical forests. Anthropogenic disturbance in these watersheds has apparently increased the spatial heterogenity of the forest. The success of both natural and induced regeneration in the area suggests that the impact of human disturbance was greater on forest structure than on its long-term productivity.

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INTRODUCTION

Development and productivity of tropical forests, like other ecosystems, are closely linked with physical and chemical processes acting on the landscape. However, the existing state of an ecosystem is often influenced by historical disturbance. Furthermore, the apparent impacts of current land uses, the recovery of an ecosystem following disturbance, and the effectiveness of conservation measures must be gauged not only by the ecosystem's present status, but also by the sequence of historical events contributing to that status. Therefore, determining the historical events that have affected the landscape is a necessary prerequisite for understanding and managing ecosystems.

This paper summarizes the physiographic setting and historical uses of the Bisley experimental watersheds in the Luquillo Experimental Forest (LEF) of Puerto Rico (fig. 1). These watersheds are the focus of a long-term ecological and silvicultural research program initiated by the Institute of Tropical Forestry in cooperation with the University of Puerto Rico's Center for Energy and Environment Research. This paper is intended to provide background information for these long-term studies.

LOCATION

The Bisley experimental watersheds are a series of adjacent drainages in the northeast section of the Luquillo Mountains (fig. 1). Situated in the northeastern corner of Puerto Rico (Lat. 18°18' N.: Long 65°50' W.), the crest of the mountains is about 9 km from the Atlantic Ocean. Over a distance of approximately 7.5 km, the mountains rise from 100 to 1,075 m in elevation. This rapid increase in elevation is accompanied by systematic changes in climate, soil, and the structure and species composition of the vegetation (Brown and others 1983). In general, as elevation increases, mean annual precipitation increases and vegetation cover changes from plantations and secondary tabonuco (*Dacryodes excelsa)* forests to primary tabonuco, colorado *(Cyrilla racemiflora),* and ultimately dwarf type forests.

The climate in the Luquillo Mountains is characterized by both local convective storms and mesoscale atmospheric disturbances. The principal weather systems affecting the level of the moist layer in Puerto Rico are: 1) easterly waves, 2) polar troughs, 3) shear lines, and 4) tropical storms (Odum and others 1970b). Summer regimes usually have deep easterly trade winds that extend into the stratosphere. Winter regimes commonly have westerly winds above 3,000 m.

Hurricanes and severe tropical storms are common phenomena and occur mainly during the late summer months. More than 70 severe storms have occurred in Puerto Rico since the early 1700's (Salivia 1972). Of these storms, 13 were classified as type A hurricanes (cyclonic events that pass over the Island with winds in excess of 110 km/h). However, only four of these hurricanes passed directly over the Luquillo Mountains.

The recurrence period of type A hurricanes decreases with increasing distance from the forest (fig. 2). Hurricanes can be expected to pass directly over the forest once every 62 years and pass within 60 km once every 22 years. Observations after the 1956 hurricane passed over Puerto Rico indicated that no appreciable damage to the forest occurred beyond 43 km of the storm's center (Wadsworth and Englerth 1959). Although the impact of a hurricane will vary with storm intensity, locale, and antecedent weather conditions, figure 2 indicates that the Luquillo forests will be directly effected by a type A hurricane at least once every 20 to 30 years.

Observations from long-term vegetation plots within the forest indicate that both forest age (Weaver 1986; Lugo and Battle 1987) and forest structure (Weaver 1986; Crow 1980) can be influenced by hurricanes. Furthermore, the last severe hurricane, which occurred in 1932, left an apparent imprint on the structure and age of the forest. Additional storms of smaller magnitude than a type A hurricane, but with higher return frequencies, can also affect the forest ecosystem.

Within the forests, climate is strongly influenced by altitude. Average annual rainfall increases with elevation from about 2,600 mm/yr at the base to a

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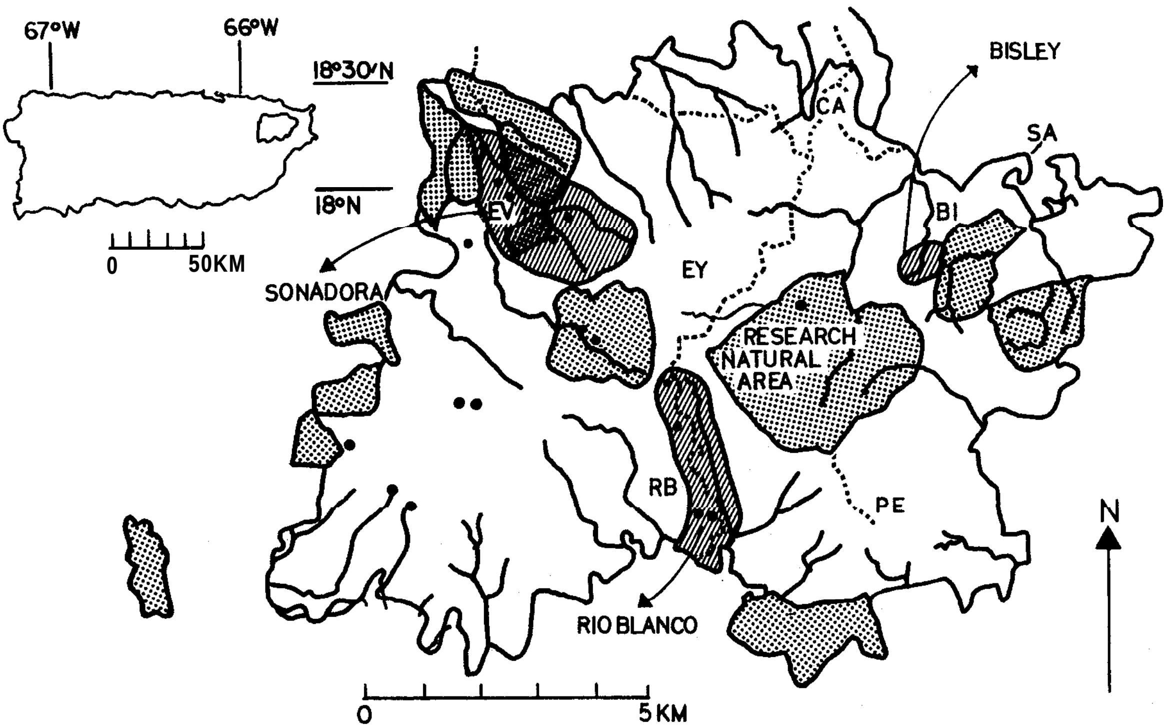

Figure 1.— *Map of the Luquillo Expermental Forest showing 12 reserved research tracts (dotted areas); Bisley, Sonadora, and Rio Blanco watersheds (shaded areas); long-term growth plots under study by the Znstitute of Tropical Forestry (points); and other sites for which long-term data sets exist (EV = El Verde, CA = Catalina, BZ = Bisley, SA = Sabana, EY = El Yunque, RB = Rio Blanco, and PE = Pico del Este). The inset shows the location of the LEF in Puerto Rico.*

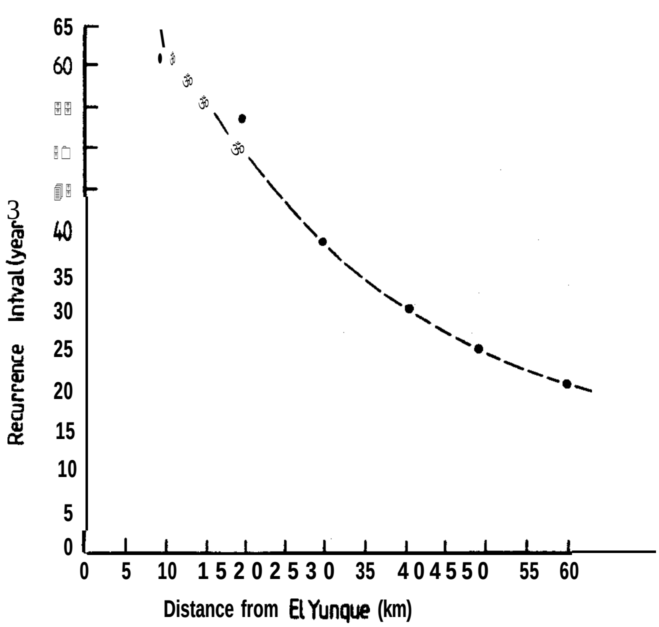

Figure 2.— *Estimated recurrence interval of type A (severe) hurricanes passing within a given distance from the center of the LEF. The figure is based on trajectories of type A hurricanes from 1700 to 1970 (Weaver 1986).*

maximum of nearly 5,000 mm/yr at the summit (Brown and others 1983). Over the entire mountain range, rainfall is distributed fairly evenly throughout the year and averages approximately 3,500 mm/yr (Lugo 1986). At the Bisley watersheds the mean annual rainfall averaged 2,887 mm/yr between 1973 and 1979 (Snyder and others 1987) and 3,242 mm/yr between 1985 and 1987 (Bosch, unpublished data). These periods, the only years recorded to date, contained one unusually dry year, 1975, and one unusually wet year, 1987. Based on long-term regional data (Lugo 1986) the mean annual rainfall at the watersheds is estimated at 3,500 mm/yr. This amount of rainfall places the watersheds in the subtropical wet forest life zone *(sensu* Holdridge 1967).

The Bisley watersheds are within the Rio Mameyes drainage system, one of the six major streams whose headwaters begin in the Luquillo Mountains. A U.S. Geological Survey stream gauge is located on the Rio Mameyes about 2 km downstream from the watersheds. The 8-year average daily discharge for this station is 1.64 m^3/s, or 2,898 mm/yr (U.S.G.S. 1987). Extremes for the period range from 0.144 to 561 m^3/s. The estimated annual runoff for the entire Luquillo Mountains is 2,052 mm/yr, or greater than 58 percent of the total precipitation (Lugo 1986).

GEOLOGY

The Island of Puerto Rico is a rugged mountain mass that has been described as a geologic "heap of volcanic debris" (Hodge 1920; Mitchell 1954). The core of the Island is an east-west trending body that was formed in association with Cretaceous and Tertiary volcanoes. Tilted beds of clastic and carbonate sediments flank this core and form an apron-like structure that becomes progressively younger as it spreads toward the coast.

Like other islands in the Greater Antilles, Puerto Rico is part of a large volcanic island-arc complex that rests along the junction between the American and Caribbean crustal plates. The region's geologic history is a complex sequence of accretionary and fragmentary events that occurred during the separation of North and South America (for review see Rosen 1985). During its development, Puerto Rico has undergone a full cycle of mountain development and is now relatively stable (King 1977).

Compared to the Islands of Hispaniola and Cuba, faulting and the formation of large valleys have played a relatively minor role in the geologic history of Puerto Rico. Nevertheless, two distinct northwest trending fault zones exist and divide the Island into three major structural blocks (fig. 3). The Sierra de Luquillo forms the core of the northeastern structural block. The southern margin of the asymmetric Luquillo range is formed by a fault-line scarp that separates the northeastern and central structural bodies. Along the northern and eastern flanks of the range, radiating ridges extend from the mountain into the lower lying coastal regions.

The majority of the LEF is underlain by volcanoclastic sediments or dioritic intrusions. Both types of rock were derived from a similar andesitic magma that was active during the Cretaceous and lower Tertiary (Seiders 1971a). Following the accumulation of the volcanoclastic sediments, late Eocene or early Oligocene tectonic activity produced the dominant structural features of the mountains. The subsequent intrusion of the quartz-rich dioritic Rio Blanco complex marks the last phase of igneous activity in the area (Seiders 1971a). Since earlier intrusions were quartz poor, this last episode of igneous activity probably contained differentiated and reworked magma.

The early Oligocene tectonic activity was followed by a period of quiescence, stability and degradation. This lasted from the Upper Oligocene to Middle Miocene during which time the Caribbean plate drifted eastward and the Antilles began to take on their present configuration (Rosen 1985). Throughout this period, partial base-leveling of Puerto Rico is thought to have occurred and an upper or St. John peneplain

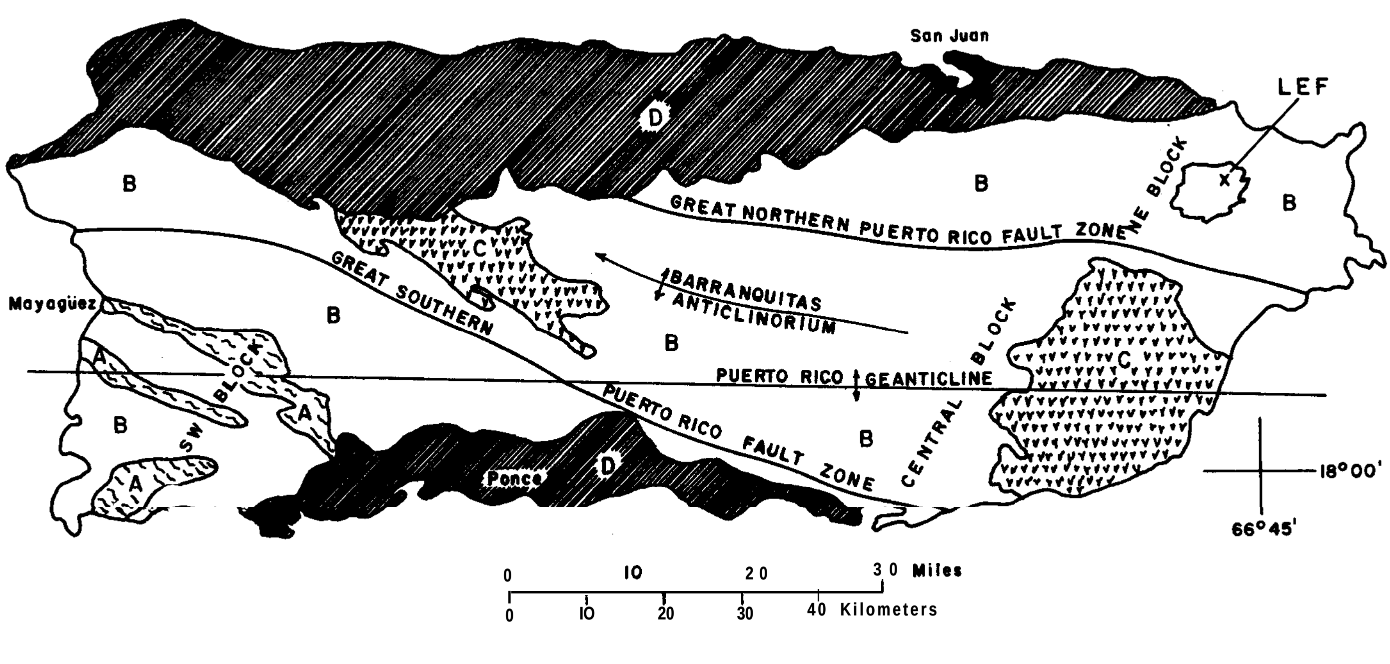

Figure 3.— *The principal geological elements of Puerto Rico. (A) Serpentine-amphibolite-chert Bermeja complex. (B) Cretaceous and lower Tertiary volcanic complex. (C) Batholiths. (D) Middle Tertiary to Holocene carbonate and epiclastic rocks and sediments. (from Glover 1971)*

developed (Lobeck 1922; Meyerhoff 1933; Beinroth 1982). St. John time was terminated in the Upper Miocene by a series of uplifts which raised the Island to its present elevation (Bienroth 1982). A second period of prolonged stability during the Pliocene is believed to have formed a second and lower erosion surface, the Caguana Peneplain. Since the end of the Tertiary, Puerto Rico has been tectonically stable. Nevertheless, Pleistocene sea levels have at various times been 25 to 65 m above present levels (Monroe 1968).

Structurally, the Luquillo Mountains are a complex terrain dominated by northwest-trending faults and associated northeast-trending folds. The major structural features in the northern section of the mountains are two broad, northeast trending folds: the Rio Canovanas syncline and the Luquillo anticline (Seiders 1971b). The area between the fold axes is largely underlain by northwest dipping beds that are cut by faults of small to medium displacement. The Bisley watersheds drain the flank of a faulted regional homoclinal structure and are cross-cut by northwest-trending faults and joints (Briggs and Aquilar-Cortes 1980).

The southern section of the Luquillo mountains is dominated by the dioritic Rio Blanco complex. The rectilinear outline of this intrusion suggests its emplacement was influenced by Northwest-trending fractures and northeast trending bedding (Seiders 1971a). Although the emplacement of the stock produced little or no folding in the adjacent host rocks, a zone of contact metamorphisms surrounds the stock. Many of the large landslides in the LEF are associated with this contact zone.

Bedded volcanoclastic rocks underlie the watersheds and most of the northern Luquillo Mountains. In the Bisley area, these sedimentary rocks are members of the lower Cretaceous, Albian age, Fajardo Formation (Briggs and Aquilar-Cortes 1980). The source of clastic sediment for these rocks was an active volcanic complex standing at or near sea level (Seiders 1971b). Debris from these volcanoes was deposited in moderately deep water after being transported and reworked by submarine slides, turbidity currents, ash flows, and falls. Alternating episodes of rapid volcano-elastic deposition and slow pelagic sedimentation resulted in a net accumulation of approximately 7,600 m of sediment (Seiders 1971b).

The bedrock underlying the experimental watersheds has been mapped as the Upper thick-bedded tuff unit of the Fajardo Formation (Briggs and Aquilar-Cortes 1980). This unit consists of thick-bedded, very dark to light-bluish gray and dark-greenish-gray tuff which is interbedded with thick-bedded to massive tuff breccia and thin to thick-bedded tuffaceous sandstone. The typical thick-bedded tuff weathers to an olive gray color, whereas the tuffaceous sandstone weathers to a pale-brown color. The total thickness of this unit ranges from 800 to 1,100 m.

Within the experimental watersheds, outcrops of bedrock are generally limited to the headwaters of the main stream channels. The dominant exposures are thick-bedded tuffaceous sandstones that are saprolitic and riddled with clay-lined faults and joints. Primary sedimentary structures are difficult to distinguish, but conglomeritic lenses and well indurated siltstone beds are definable. Relic grains of plagioclase and mafic minerals are recognizable in some hand specimens. Weathering of these mafic, quartz-poor rocks produces a clay-rich, sand-poor residum. However, where outcrops are broken by intersecting joint planes, resistant angular boulders can be formed. The size and shape of these boulders is similar to those found along stream channels and drainages.

PHYSIOGRAPHY

The first detailed studies of Puerto Rican physiography divided the Island into four landscape units (Lobeck 1922; Meyerhoff 1927). These units were based on the presence of areas of coincident mean elevation. In order of decreasing elevation, these erosional landscapes were named 1) the Upland Monadocks 2) the St. John peneplain, 3) the Caguana peneplain, and 4) the Lower peneplains. In his survey of the geology of Puerto Rico, Mitchell (1954) eliminated the Lower peneplain and distinguished four additional physiographic regions: 1) the Belted Coastal Zone, 2) the Interior Lowlands, 3) the Playas, and 4) the Alluvial Plains. In the latest survey of Puerto Rican landforms, Monroe (1980) identified three major physiographic divisions: 1) the Upland Province, 2) the Norther Karst Province, and 3) the Coastal Plain Province. All of the physiographic interpretations have identified the Luquillo Mountains as part of the Upland Province.

The Bisley watersheds drain a highly dissected, mountainous terrain. Steep gradient streams, amphitheater-shaped first and zero-order valleys, and "cuchillo" or knife-like divides characterize the landscape (figs. 4 to 7). Traditionally, the study area was considered a mature stage (*sensu* Davis 1909) transition zone between the erosion resistant Luquillo Mountains and the dissected St. John and Caguana peneplains (Lobeck 1922; Meyerhoff 1927; Bienroth 1969; Pico 1974). However, the early interpretations could not explain why the Luquillo Mountains were resistant to erosion when similar rocks decompose rapidly in other humid areas of Puerto Rico (Meyerhoff 1927). Recent interpretations consider the mountain range to be a tilted fault block that shows the

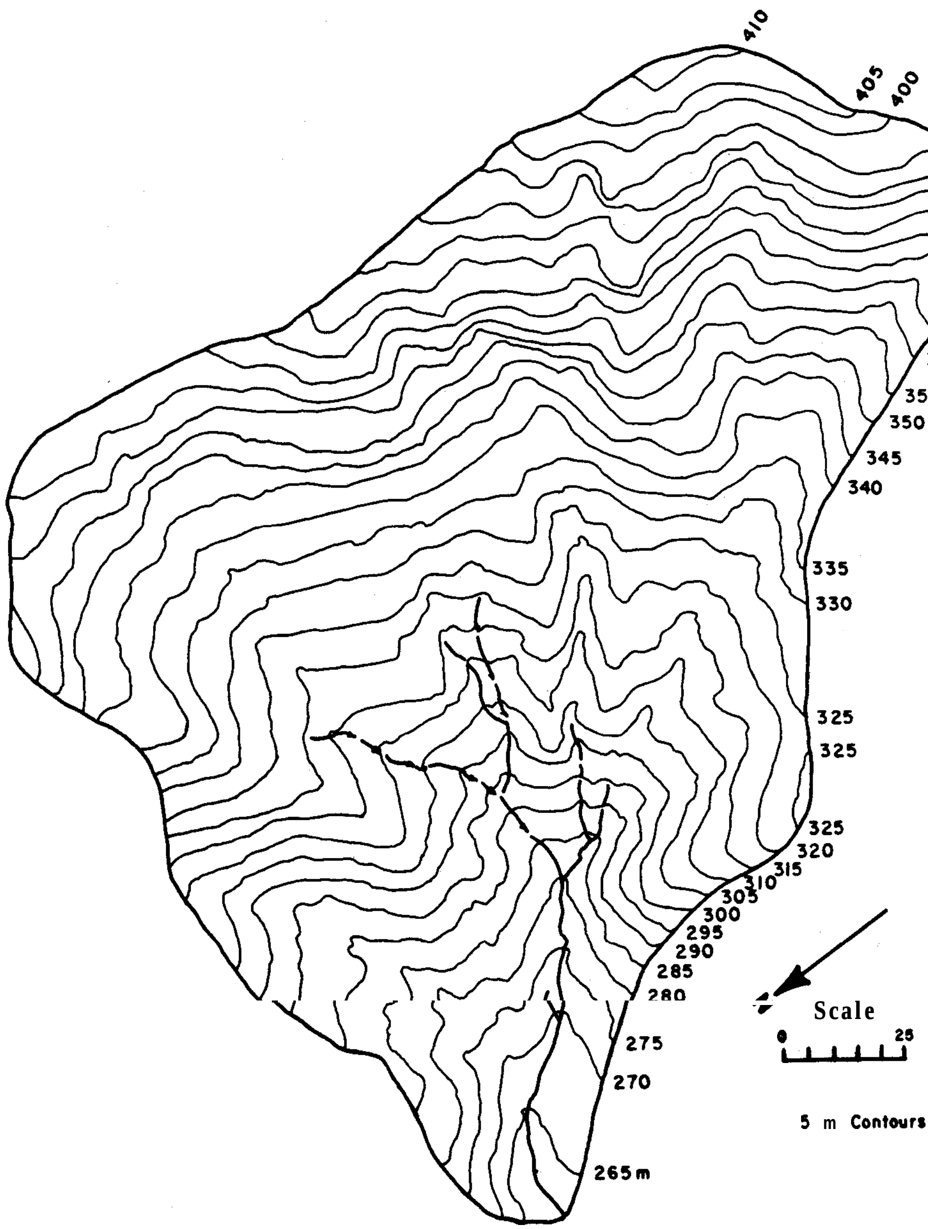

Figure 4.— *Topographic map of watershed 1.*

effects of erosion (Monroe 1980), rather than the resistant remains of a former land surface.

Hillslopes within the study area are generally convex-concave in form and have characteristics described in other humid tropical landscapes (Imeson and Vis 1982a, 1982b; Besler 1987). The middle segments of the typical hillslope profile are straight. Upper segments are convex and pass into narrow, well defined divides. Lower slope segments are concave where they pass into first-order valleys and straight where they-join the main stream channel. Although there are occasional outcrops of bedrock, and boulders are commonly strewn across the landscape, a surficial mantle of clayey soil or colluvium predominates. These slopes can be considered highly cohesive *(sensu* Strahler 1950) because the surficial mantle has an angle of repose greater than the repose angle of loose, dry granular material.

The boundaries of the experimental watersheds are defined by narrow ridges topped by some of the largest tabonuco trees in the drainage. These narrow divides have slightly convex side slopes, are well drained, and have relatively well developed soils. Away from the divides, the slopes are broad, slightly concave, and are drained by a dense network of swales and intermittent streams. Although patches of bare soil are common, most slopes are covered with a thin layer of leaf litter.

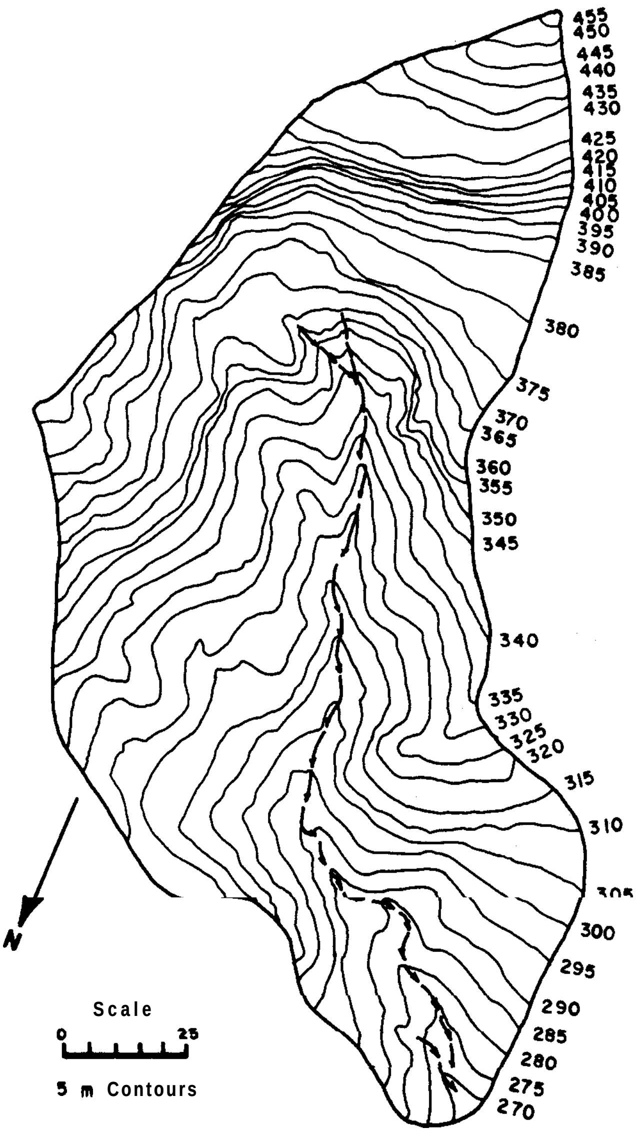

Figure 5.— *Topographic map of watershed 2.*

The frequency distributions of slope angles in Bisley watersheds 1 and 2 approximate normal distributions (fig. 7). The symmetrical distribution of angles suggests a uniformity of slope processes at the drainage basin scale. Nevertheless, the wide dispersion about the mean slope angle indicates a range of local processes and conditions. Over 50 percent of the drainage area has slopes greater than 45 percent, whereas 85 percent of the slopes are less than 70 percent. For comparison, about 75 percent of Puerto Rico consists of either mountains or hills, and almost 25 percent consists of steep slopes of 45 degrees (100 percent) or more (Pico 1974). At the El Verde field station in the northwestern portion of the forest, only 20 percent of the area has slopes over 45 percent (Asbury and Lodge, unpublished data).

The physical processes acting on these hillslopes include soil creep, shallow earth movements, tree throws, and debris flows. Soil creep, the combined processes that result in the slow downslope movement of surficial material, has been measured in other parts of the LEF (Lewis 1974, 1976). Within the experimental watersheds, inclined trees and thick colluvial deposits suggest that creep is an active process. Rectangular holes, commonly 1 to 2 m wide and 0.5 to 1 m deep, produced by tree throws are also common features in the watersheds.

Debris flows and shallow earth movements appear to be as important in the Bisley watersheds as they are in other parts of Puerto Rico. Recent landslides in the watersheds and adjacent forest have created crescent-shaped hillslope scars similar to features of other humid forests (Hack and Goodlett 1960) and other areas of Puerto Rico (Jibson 1987). These failures are typically at the fluid end of the spectrum of land movements and consist of poorly sorted slurries of rock, soil, and water.

A reconnaissance survey of failures produced by the December 1987 rains indicated that the slurries produced by these failures are commonly transported considerable distances. For example, 80-m^3, highly fluid earth movement occurred in experimental watershed 2. The slurry produced by this failure traveled 25 m, or 5 times the length of its headcut, to the adjacent stream channel. In another slide observed on Commonwealth RT. 966, a tree fern was transported in an erect position for almost 20 m.

First-order stream valleys are amphitheater-shaped and similar to hollows of other humid forested environments (e.g., Hack and Goodlett 1960; Hupp 1986). Nearly vertical headwalls, steep side slopes, and concave longitudinal profiles characterize these valleys. Typical valley headwalls have vertical faces of bare or moss-covered soil and colluvial footslopes. The central part of the valleys are saturated areas that drain into well defined but intermittent stream channels. Floors of the larger valleys are armored with cobbles and boulders. Between the veneer of boulders are saturated patches of gley-type soils and accumulations of organic matter. These valleys accumulate water from the adjacent hillslopes and the chutes and swales that drain into them; Vegetation within these valleys is dominated by palms *(Prestoea montana)* and ferns.

The drainage network in the watersheds consists of steep gradient boulder streams supported by a dense network of ephemeral channels. The drainage pattern is dendritic in form and can be divided into three morpholgical types: 1) boulder-lined main channels, 2) intermittent channels lined with moss-covered cobbles, and 3) leaf-tilled swales (fig. 8). At a scale of 1:500, the boulder-lined main channels of watersheds 1 and 2 are fourth-order streams *(sensu*

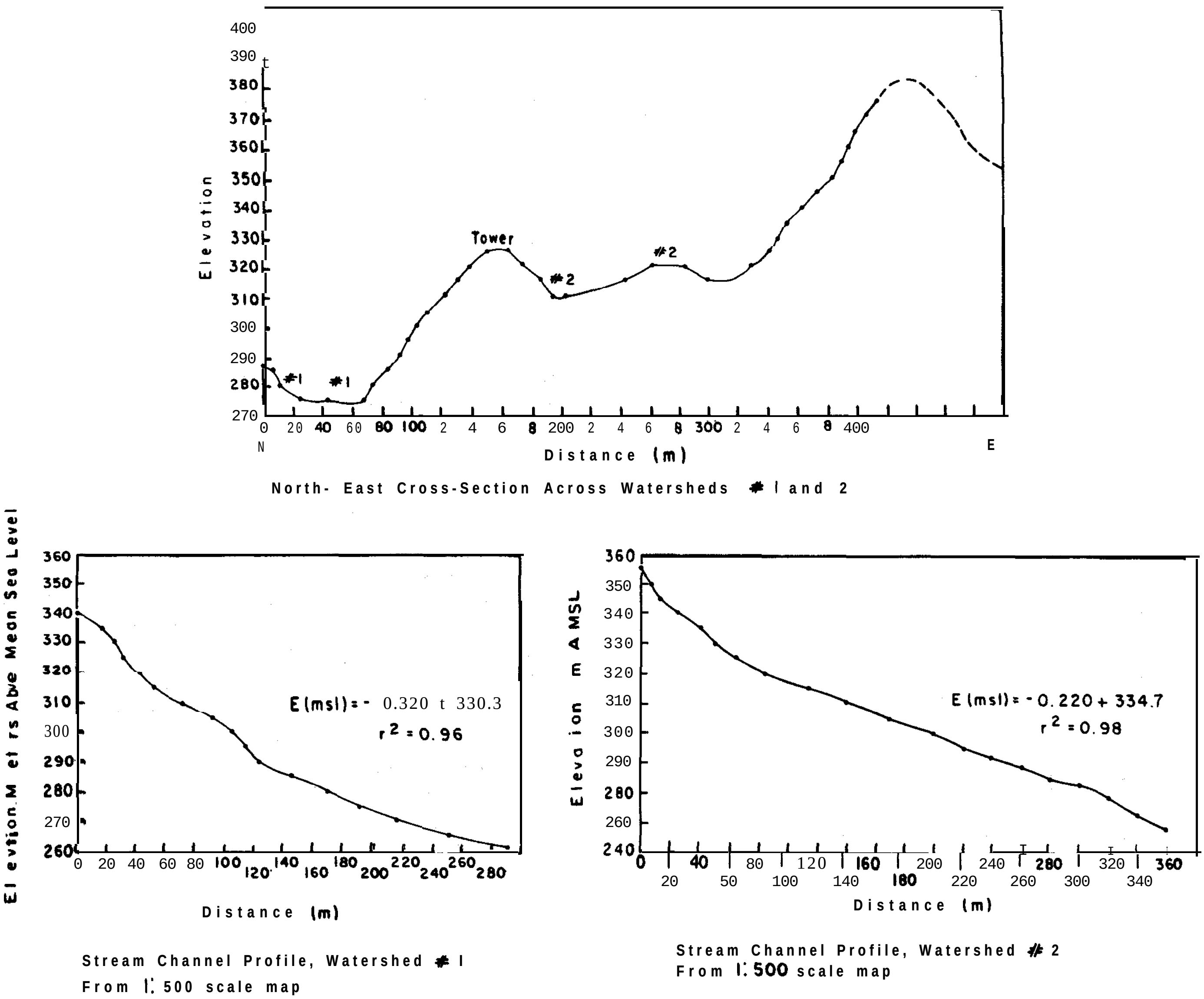

Figure 6.— *Topographic cross-sections across watersheds 1* and 2 *and stream channel profiles of watersheds 1 and* 2.

Strahler 1952; table 1). Tributary junctions between main channel segments are typically graded. First-order channels are either graded to small floodplains along the main channel or enter the main channel at a slight elevation.

Third- and fourth-order channels of the experimental watersheds are steep gradient boulder-lined streams. The longitudinal profiles of these channels are concave in form and steepest where the stream flows over bedrock. Waterfalls are common, whereas pool and riffle sequences are poorly defined. Both high-flow channels and small saturated floodplains occur adjacent to the active channel. Channel boulders are well rounded and occasionally several meters in diameter.

Intermittent first-order channels are typically lined by plastic clay and moss-covered boulders. Although these channels are intermittent and have flowing water only during and immediately after storms, they are sufficiently active to prevent the establishment of vegetation or the accumulation of a litter mat. Feeding into these intermittent channels are 1- to 2-m-wide swales that are armored with fine-root mats and filled with moist leaves and occasional saplings. These swales are definable up to watershed divides and are so numerous that in places they form a corrugated surface on the upper slopes of the basins. Although these channels are well defined, fluvial or debris flow erosion within them is infrequent enough that thick accumulations of leaves can devel-

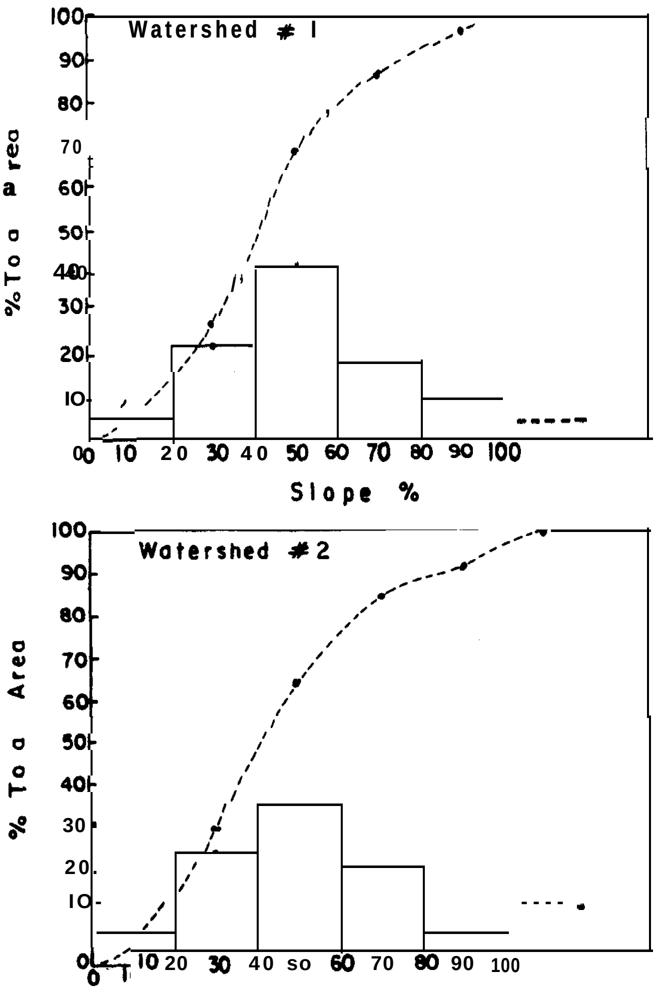

Figure Y.-*Frequency distribution of slope angles in watersheds 1 and 2.*

op and understory vegetation can become established.

At a scale of 1500, the watersheds follow the geometric laws of stream order and number (table 1). Nevertheless, neither relationship is statistically strong, and the number of first-order streams is larger than predicted. However, this is to be expected in small, highly dissected drainages (Leopold and others 1964). In general, Bisley watersheds 1 and 2 have similar morphological characteristics (tables 1 and 2). The largest difference between the two basins is in the width/length ratio.

SOILS

The soils in the Bisley experimental watersheds are typical of areas in the Luquillo forest that are underlain by volcanoclastic sandstones. The dominant pedon is a isohyperthermic soil derived from a clay-rich residum. These soils are classified as Ultisols and are clayey, highly leached, and well weathered. Gley and stoney type soils also occur within the drainage.

Soils in the LEF were first mapped at a scale of 150,000 (Roberts 1942). At that time, soils in the Bisley area were grouped with other deep humid upland soils of Puerto Rico and were mapped as the Los Guineos series. The most recent soil survey (scale 1:20,000) was published in 1977 by the USDA Soil Conservation Service (Boccheciamp 1977). During this survey the soils were further subdivided and mapped as the Los Guineos-Yunque-Rock Land association. The Luquillo forest soils are currently being remapped, and soils in the Bisley area are being reclassified as the Humatus-Zarzal-Cristal complex (L. Huffacher 1987, personal communication).

Soil characteristics in the Bisley area are strongly related to local topography and drainage. Humatus soils are moderately well drained and occupy stable upland surfaces. Sideslope soils are the most common and have been classified as Tropohumults (Boccheciamp 1977). These are generally clayey soils with moderately developed, coarse, subangular blocky structure. They have high available water capacity and well developed mottles. Based on distinct variations in mottles and soil development, these soils can be subdivided into two associations: Zarzal and Cristal soils. Depressions and other saturated areas have gray, gley-type soils. Stoney soils occur in headwater areas and along drainages.

Except for stable upland areas, these soils are generally unsuited for cultivation (Boccheciamp 1977). The main restrictive features of these soils are excessive local relief, seepage, high clay content, and the presence of surface stones. In addition, these soils are highly erodable when the vegetative cover is removed. The characteristics of individual soil types in the watershed are discussed below.

Zarzal Soils.-These are the driest of the sideslope soils and the dominant pedon in the experimental watersheds. These soils occur on steep to very steep, convex and middle sideslopes. The solums are well drained, typic Tropohumults that form on residum and colluvium of the volcanoclastic sandstones. The subsoil is dark yellowish-brown clay, whereas the substratum is a strong brown stoney clay loam. Red mottles and small black iron-mananese concretions are common in the lower portions of the subsoil. However, the low chroma mottles that characterize the Cristal soils are absent.

Cristal Soils.-These soils occupy the lower sideslopes of the watersheds and are in topographic positions that receive additional water through subsurface flow and upland runoff. They are somewhat poorly drained and have well developed low chroma mottles (white and gray) in addition to the red mottles common to the Zarzal soils. Typically, the upper

Figure 8.—*Bisley stream channels. (A) Main channel of watershed 1. (B) intermittant channel. (C) Leaf-lined swale. (D) Banana trees along main stream channel of watershed 1.*

Table 1.-*Morphologic characteristics and geometric relations among stream order, length, and number in Bisley watersheds 1/watershed 2*

Morphologic characteristics [1]				
Stream order[2]	Number	Length (m)	N_o/N_{o+1}	L_o/L_{o+1}
1	15/11	31/29	3.8/2.8	0.49/0.50
2	4/4	64/57	2/2	1.2/0.9
3	2/2	55/67	2/2	0.45/0.42
4	1/1	120/161	...	...
Total	22/18	270/314	...	...
Average	...	...	2.6/2.3	0.71/0.61

Geometric relations[1]	
Watershed 1	Watershed 2
$Lo = 30.9(So)^{0.83}$	$Lo = 26.92(So)^{1.11}$
r = 0.89	r = 0.94
$No = 15.14(So)^{-1.93}$	$No = 11.7(So)^{-1.69}$
r = -0.99	r = -0.99

[1]No = stream number; Lo = stream length in m; So = stream order.
[2]*Sensu* Strahler 1952. First-order streams are defined as intermittent stream channels on 1:500 scale map and do not include leaf filled swales.

Table 2.-*Physical characteristics of Bisley watersheds 1 and 2*

Characteristic[1]	Watershed 1	Watershed 2
Drainage area, A (ha)	6.70	6.34
Maximum elevation, H (m)	410	450
Minimum elevation, h (m)	261	267
Total basin height, H-h (m)	149	183
Relative basin height, b/H	0.64	0.59
Maximum basin length L(M)	328	455
Maximum basin width, W(m)	341	170
Length/width ratio, L/W	0.96	2.67
Relief ratio, H-b/L	0.45	0.40
Main channel gradient, (m/m)	0.28	0.24
Stream frequency, F = N/A (N/ha)	3.3	2.8
Drainage density, D = SL/A (m/ha)	141.9	132.7

[1]SL = total stream length; N = total stream number; A = area.

part of the subsoil is 80 cm thick, mottled pale brown clay that grades with depth to mottled strong brown clay.

Humatus Soils.-Moderately well drained, stable landscape positions on upland surfaces have small patches of Humatus soils. These profiles typically have a yellowish-brown surface soil and yellowish-red, friable clay at depth. The well developed mottles that characterize the Cristal and Zarzal soils are absent in this pedon.

Rough Stoney Land.-Areas with greater than 20 percent stone rubble surfaces are also common in the experimental watersheds. These cobble- and boulder-covered areas are typically at heads of drainages or along water courses. The soils in these areas occur between and beneath the rubble surface and are highly variable. The surface layer is commonly a thin, dark-grayish brown plastic clay containing abundant leaf litter. Subsoil is either well mottled clays of the Cristal series, or gley-type soils. Stoney land has been identified in other areas of the forest where in some places a person can travel for several hectometers by stepping from stone to stone (Roberts 1942).

Gley Soils.-In areas of excess soil moisture, gley structureless soils are common. These soils typically are at the heads of drainages, adjacent to stream channels, and in footslopes below eroding hillslope scarps. Gley soils are commonly, but not exclusively, associated with stoney land., The typical subsoil is structureless, gray, plastic, heavy clay 1 to 20 cm thick. Beneath the gley surface, horizons range from bluish gray to mottled rusty brown. In some areas, the gley soils cap relatively unaltered Cristal soils.

VEGETATION AND BIOMASS

The Bisley watersheds are within the tabonuco forest ecosystem and are covered with secondary tabonuco type forests. In general, tabonuco forests cover 51 percent of the LEF (Brown and others 1983). Approximately 32 percent of these forests are in an advanced stage of natural regeneration. Like other advanced secondary forests in the region, the watersheds have never been completely cleared and have a structure and composition resembling their primary counterparts.

The structure of the forest can be divided into four strata: a discontinuous upper stratum, a second continuous canopy at 20 m, understory, and ground level herbs and shrubs. The ground level herbs and shrubs are only important in openings where direct sunlight reaches the ground. The average leaf-area index for the Bisley forests is estimated at 6.4 (Odum and others 1970a) and is intermediate among the values reported for other forests and plant communities.

The first system-level estimates of biomass and chlorophyll in the LEF were made in the Bisley sector, about 0.2 km due east of watershed 1 (Odum and others 1970a). These measurements were made to delimit the magnitudes of the tropic compartments and portray an overall view of the forest. In summary, the majority of the biomass is contained in leaves and plant material (table 3).

Chlorophyll A content was fairly uniform per area of leaf surface (0.2 to 0.4 g/m^2; table 4). Nevertheless, when variations in leaf area in the forest were accounted for, Chlorophyll A content varied from 0.8 to 4.5 g/m^2 of level forest floor. This variation resulted from the wide range of leaf area with topography. Small leaf area index's were found in ravines and openings. Large indices occurred on ridges. Nevertheless, the composite chlorophyll contents of herbaceous, understory, and crown vegetation are similar.

Table 3.—*Principal compartments of biomass in the Sabana/Bisley area*[1]

Compartment	Biomass (g/m^2)	% of Total
Leaves, dry	812	99.2
Animal biomass	6.6	0.8
Carnivors	1.0	0.1
Total	819.6	100

[1]From Odum and others 1970b.

LAND USE HISTORY

At the time of European discovery, the Bisley watersheds, like most of Puerto Rico, were forested. Although pre-Columbian agriculturists cleared small tracts of land in the mid-altitude forests of Puerto Rico, their activities probably had little impact on the vegetation of the Luquillo forests (Wadsworth 1949). The coastal plains and the drier intermountain valleys were better suited to their needs than the Luquillo range. The Indians did leave rock carvings in the Mamayes and Sabana valleys and used the mountains as a haven during their early battles with

Table 4.—*Chlorophyll A content per area of leaf surface in the Sabana/Bisley area*[1]

Species and other sources	Chloro. A (g/m^2)	Species and other sources	Chloro. A (g/m^2)
Piper aduncum	0.330	*Myrcia deflexa*	0.40
Palicourea crocca	0.343	*Brysonima*	0.360
Marcgravia	0.177	Liken on trunk	0.021
Anthurium	0.41	Moss on trunk	0.052
Sloanea berteriana		*Philodendron*	
Shaded seedlings	0.18	Leaves	0.314
Shaded understory	0.29	Liana stems	0.200
Magnolia splendens	0.50	*Dacryodes excelsa*	
Manilkara bidentata	0.40	New leaves	0.14
Didymopanax morot.	0.33	Shaded seedlings	0.38
Myconia prasina		Shaded understory	0.40
Shaded seedlings	0.187	Crown	0.37
Shaded understory	0.27	*Cordia borinquensis*	0.33
Crown	0.22	*Genipa americana*	0.27
Cecropia peltata	0.12	*Octea leuxoclon*	0.48
Cyathea pubescens		*Oxandra laurifolia*	0.29
Shaded seedlings	0.34	*Prestoa montana*	
Shaded understory	0.28	Shaded seedlings	0.25
Crown	0.36	Crown	0.73
Brown forest floor litter	0.10	Ground fern	0.188
Coccolobis		Bromeliads	0.110
Shaded understory	0.43	*Musa cavendishi*	0.36
Crown	0.34	Algae on live snail	0.041
Composite value for herbaceous and ground vegetation			0.30
Composite value for understory			0.34
Composite value for crown vegetation			0.37

[1]After estimates by Odum and others 1970b.

the Spainards. Nevertheless, any impact on the Bisley area by Indians was apparently negligible.

With European colonization, the clearing of land and the extent of human-induced disturbances increased. The rate of landscape transformation was initially very rapid but slowed with the development of the continental New 'World. Columbus brought cane sugar to the Caribbean on his second voyage in 1498. Within 35 years, Puerto Rico had 10 sugar mills that produced about 155 tonnes of sugar per year (Williams 1970). At the same time there were 30 sugar mills on the Island of Jamaica.

The rapid transformation of the Puerto Rican landscape immediately following discovery did not continue. The first two major settlements, Caparra and San German, were established by 1510, but a third town was not established for another 136 years. Additional towns that began to be formed during the preceding century was officially founded in the late 17th century. During these first 3 centuries of colonization, the relatively inaccessible nature of the Luquillo Mountains limited utilization. Although agricultural settlements did exist in the foothills of the mountains, most of the early European impact on the landscape occurred in the coastal areas and intermountain valleys.

By 1899, the population densities of the coastal regions and lower flanks of the Luquillo Mountains ranged from 40 to 100 people/km^2 (Pico 1974; calculated from 1899 U.S. Census). Population densities in these areas remained under 120 people/km^2 until the 1930's. In 1980, over 220 people/km^2 lived in the region (U.S. Census 1980). Corresponding to this increase in population there has been a shift in land use from agriculture and forestry to residential and recreation.

The sections of the LEF that contain the Bisley watersheds were purchased by the U.S. Forest Service in the mid-1930's. This area was not included in the original Spanish Crown Lands and had been cultivated and commercially logged before the purchase. However, at the time of the purchase, the Bisley area was less disturbed than other areas along the flanks of the Luquillo Mountains (Marrero 1947).

Land use in the Bisley area can be divided, for convenience, into three activities: 1) mining, 2) agriculture, and 3) timber management. The impact of these activities is discussed below. In addition, a chronology of historical events that have impacted the area since European settlement is included in the Appendix and summarized in figure 11.

Mining Activity

During the first decades of European settlement, gold mining was a major activity in Puerto Rico. In 1513, the extraction of gold from placer deposits began in the coastal regions south of the Luquillo mountains, in the vicinity of Naguabo. However, within 20 years of the initial activity, mining began to decline (Wadsworth 1970a; Cardona 1984). This decline resulted from lack of labor, discovery of rich mineral deposits in South America, damage left by several tropical storms, and Carib Indian attacks. Within the present boundaries of the LEF, the greatest mining activity occurred during the 19th century.

Mining in the Luquillo Mountains has been centered around the extraction of gold and copper. The richest gold deposits were in the drainages of the Mameyes and Sabana Rivers. The best copper deposits were found in association with the Rio Blanco diorite. Copper deposits were mined from the mid-1860's to the end of the 19th century (Wadsworth 1970a). Large-scale gold mining operations were attempted in 1842, 1870, 1903, and 1934 (Wadsworth 1949; Cardona 1984). However, these projects either were never fully established or were abandoned after a few years. Nevertheless, small scale placer mining operations remained active, particularly during economic depressions. In 1899, 56 gold and silver miners were working in eastern Puerto Rico, and a "considerable" number of prospectors worked on the mountain in the 1930's (Wadsworth 1949). At least one miner was actively prospecting in 1987.

Between 1800 and 1903, 11 placer mines were active along the Rio Mameyes, due west of the watersheds (Cardona 1984). The most productive mines were in drainages mineralized by igneous intrusions. Because the Bisley watersheds drain relatively unaltered volcanoclastic sandstones, it is unlikely that any mining operations occurred within the experimental drainages. Furthermore, there is no physical or historical evidence to indicate mining in the drainages. Nevertheless, because of their close proximity to the richest gold bearing deposits, the drainages of the watersheds were undoubtedly explored for gold. Although placer mining can significantly alter the landscape, there is no physical or historical evidence that large-scale mining occurred in, or impacted, the Bisley experimental watersheds.

In addition to gold and copper mining, quarry operations were also active in the Luquillo forest. The remains of an old quarry exist at the entrance to the Bisley watersheds along Commonwealth Rt. 88. However, this quarry, like the nearby gold mining activity, had little impact on the forests of the experimental watersheds.

Agriculture

Extensive agricultural activity did not begin in the Bisley area until the government land distribution programs of the early 1800's. Nevertheless, local agricultural activity in the Luquillo Mountains began with the advent of European settlers. In 1509, Cristobal de Guzman had a farm and 50 slaves in the Rio Mamayes drainage (Wadsworth 1949). However, his farm was burned, and he was killed during a Carib Indian attack in 1530.

In 1831 coffee was grown in the region, but most of the hinterland of Fajardo and Luquillo was forested and sparsely populated (Wadsworth 1949). Between 1830 and 1890 government land distribution programs were active in the region, and the flanks of the mountain were cultivated in coffee, bananas, and subsistence crops, including upland rice. The forest also supplied wood products and water resources to the surrounding communities.

By the mid-1800's there were clearings downstream of the watersheds, but the actual experimental drainages were forested. The first selective culling of the Bisley forest probably occurred at this time. Before this, the low demand for timber and the difficulty of extraction limited timber production. Moreover, because of the low demand, many trees were burned in place when land was cleared for coffee and agriculture (Barrett 1902; Wadsworth 1949). However, as the Island population grew and Puerto Rico was opened to the world markets, the demand for timber grew. Between 1830 and 1890 timber from the Luquillo Mountains was exported. By 1903 the entire mountainous parts of the Sabana river valley had been logged to some degree.

The amount of cultivated land in the Luquillo Mountains increased steadily from 1800 until a hurricane passed in 1899 (Wadsworth 1949). Following the hurricane, many of the damaged farms and coffee plantations were abandoned and allowed to reforest naturally. This decline in agriculture and the subsequent reforestation pre-dates the general trend of natural reforestation in Puerto Rico that began about 1950 (Birdsey and Weaver 1987).

An 86-year-old, life-long resident of the Bisley area stated that during his youth the headwaters of experimental watersheds were known as "Palo Quemado," because of charcoal production that occurred in the area. (Don Angelito Torres 1987, personal communication). Furthermore, much of the area from Sabana to the Rio Mamayes was owned by different absentee landlords who allowed families to live and work the area. Apparently, these families cultivated small patches of bananas and subsistence crops near the stream channels. The sideslopes and ridgetops were forested and cultivated with coffee. Residents also made charcoal for personal use. However, because of the inaccessibility of the area before the 1920's, charcoal was produced only for local use. The actual extent of cultivation in the experimental drainages is unknown. Nevertheless, the remains of charcoal kilns and a few scattered banana and coffee plants have been found within the drainages.

The Bisley watersheds were originally purchased as parts of U.S. Forest Service tracts 52 and 48. Both of these tracts stretched from the Rio Mameyes to areas west of the experimental watersheds (figs. 9 and 10). The lower parts of the experimental watersheds are located in the southeast corner of tract 52. Because of the general nature of the survey maps, the exact location of the experimental watersheds cannot be identified on them. Tract 52 contained 203 ha of forest and pasture and was purchased in 1936 (table 5). The headwaters of the drainages were purchased in 1934 as part of 159-ha tract 48.

The 1934 U.S. Forest Service Land Acquisition report for tract 48 indicates that only one family lived in the area at the time of purchase. This residence was in the southeast corner of the parcel and outside the drainage of the experimental watersheds (Gerhart 1934a). According to the report, 5.2 ha of pasture surrounded the residence, but the experimental watersheds were forested. Areas along the Rio Mameyes had also been cleared and were cultivated with bananas, plantains, and sweet potatoes. The "northern portion" of the tract, which would have been in the vicinity of the study area, was reported to have contained virgin stands of ausubo *(Manilkara bidentata)* (Gerhart 1934a). Although the area had been culled in the previous decades, little ausubo was removed. The acquisition report also states that the "upper portion" of the tract was "severely damaged" by the 1932 hurricane (Gerhart 1934a).

The lower elevations of tract 52, experienced greater human-induced modification than the headwater regions. At the time of purchase only one family lived in tract 52, which was locally called "La Rosario." The tract contained 86 ha (42 percent) of merchantable timber, 59 ha (29 percent) of young growth forest, and 58 ha (29 percent) of grazed or cultivated area (Gerhart 1934b). The forested portion was limited to a narrow strip along the tract's southwest boundry, in the vicinity of the watersheds. Much of this area had received a light culling in the decade before the 1934 report. This culling removed all mature ausubo and left a stand of mature and over mature tabonuco. The area outside the timbered strip was considered to have been "exploited recklessly" (Gerhart 1934b).

Coffee and bananas were planted in tract 52 in the "decades" before the 1934 evaluation (Gerhart 1934b). However, only minor crops were produced in the area after the 1899 hurricane. By 1934 all of the original coffee plantations sere destroyed, but many of the original shade trees *(Inga fugifoliu* and *Ingu vera)* remained. The sketch map that accompanies the report indicates that the central section of the tract was either cultivated in bananas or was used for grazing (fig. 10). This pastured area had patches

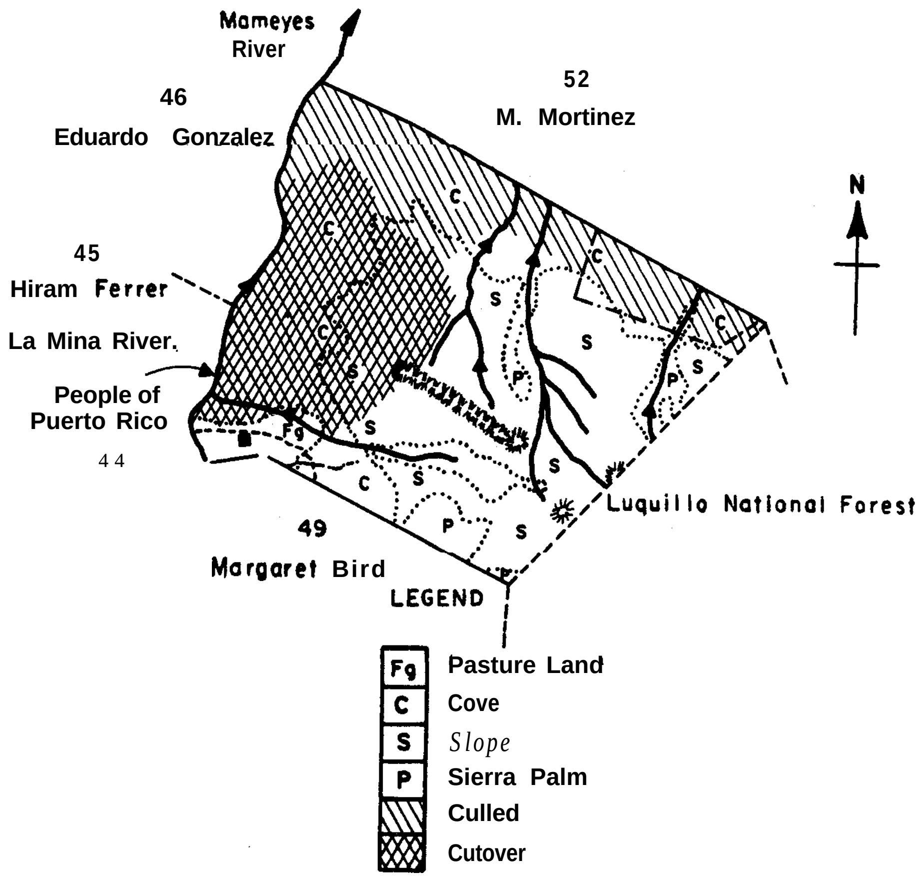

Figure 9.— *U.S. Forest Service map of tract 48 in 1934.*

Table *B.-Land classification of tracts 48 and 52'*

Location	Land type Cove	Slope	Field	Total
Tract 48 (ha)	91	64	5	160
(%)	56	40	4	100
Tract 52 (ha)	136	8	59	203
(%)	67	4	29	100

'After work reported by Gerhart 1934a,b.

of good forage species along with areas of brush. Banana propagation was encouraged in parts of the abandoned coffee plantations, while other areas were being naturally restocked with timber. Erosion on the tract was considered to be of "slight consequence" (Gerhart 1934b).

In the 1930's the Civilian Conservation Corps constructed the road and culverts that define the downstream end of the experimental watersheds. The road was constructed on an existing oxen trail that had been the main thoroughfare between Sabana and Catalina. Initially, the paved road was to continue to the Rio Mameyes and eventually to Catalina. However, only the first section of the road, the ends just past experimental watershed 3, was actually completed. At the time of construction, clumps of bamboo *(Bambusa vulgaris)* were planted adjacent to the roadside for erosion control. The abandoned dirt road that follows the upper divide of watersheds 1 and 2 may also date to this time.

The composition of the timber species of tracts 52 and 48 reflect the selective harvesting that occurred before 1934 (table 6). Tabonuco dominates the average standing wood volume in both tracts. Apparently, harvesting of ausubo and fuel woods in track 52 was so extensive that in 1934 the remaining forest was nearly a pure stand of mature tabonuco. Track 48 was culled to a lesser extent and still contained large areas of ausubo. Approximately 14 percent of the wood volume on this track was from species that indicate the Colorado type forest (Wadsworth 1970a). Conspicuously absent in both tracts are the fourth, fifth, and sixth ranking species (by volume) in a typical tabonuco forest (Briscoe and Wadsworth 1970): *Ormosia krugii, Ceropia pelata,* and

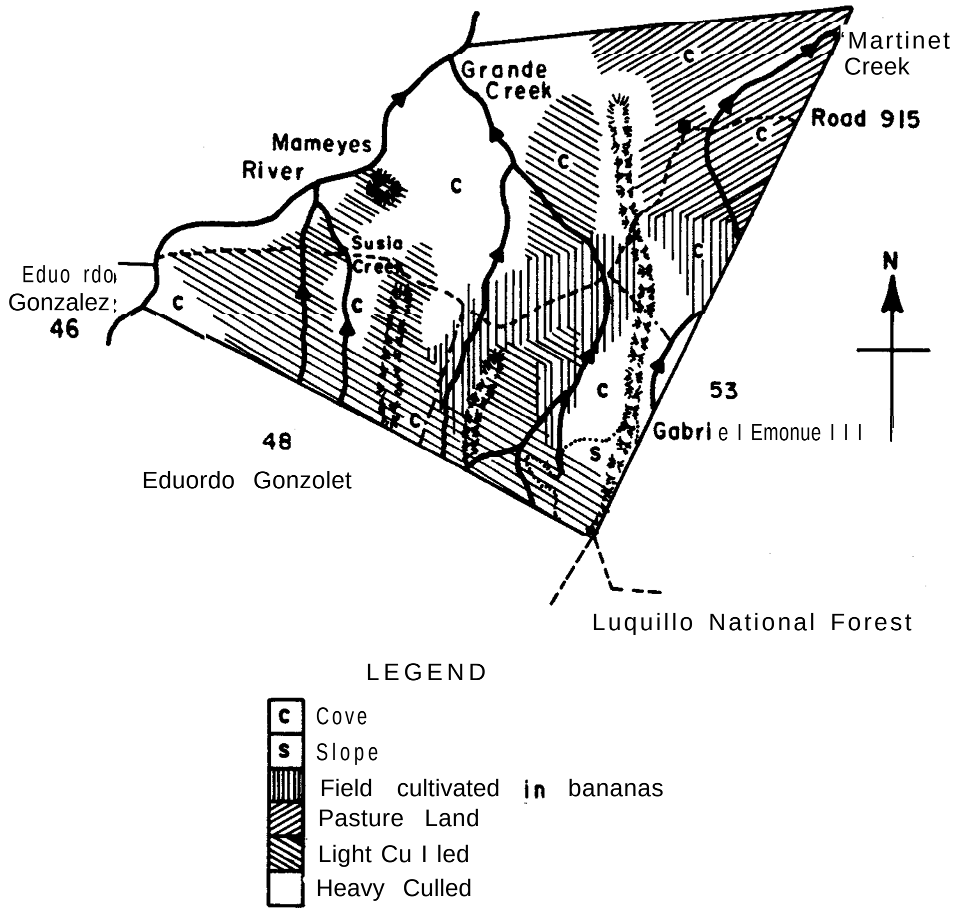

Figure 10.—*U.S. Forest Service map of tract 52 in 1934.*

Micropholis chrysophylloides, respectively. These species were probably removed for fuel wood or were not considered in the summary of timber species.

Timber Management

The first comprehensive timber management plan for the Luquillo Mountains was initiated by the U.S. Forest Service in 1934 (Munoz 1965). Prior to this, management of public lands was minimal, and most privately owned areas were either cleared for agriculture or selectively cut for desirable species. Since the initiation of timber management by the Forest Service, the planting of clearings and the silvicultural refinement of existing stands have occurred in and around the watersheds. Since 1949, the Forest Service has designated the Bisley drainages as timber lands and has implemented a variety of management activities in the area.

Logging in the Luquillo Mountains has generally been a selective process, removing different species at different times. In all logging operations the major obstacle to timber exploitation has been the transportation of logs. Until the 1940's, the typical logging operation involved skidding by a team of oxen. Ruts produced by these skidding operations can still be found in the forest today. Because skidding with draft animals is generally limited to slopes of less than 30 to 40 percent (Wenger 1984), logs on steeper slopes were sawed in place. The rough boards were then transported out of the forests, often on the heads of men. During the production of charcoal, kilns were built near felled trees to minimize the transportation of logs. Charcoal was then carried out of the forest in bags. The remains of several former kiln sites have been found in the experimental watersheds. These sites are generally within 150 m of the nearest road.

In the 1930's logging operations occurred in the Bisley area to the west of the experimental watersheds. During these operations trees were transported to the road-head past experimental watershed 3 (Don Mamaso Fuentes 1987, personal communication). During this time the timber crew of the Civilian Conservation Corps camped across the road below the watersheds, and a small supply store was located along the road between watersheds 1 and 2.

The first plantation in the region was established

Table 6.--*Timber species and their average aerial volume on tracts 52 and 48 as reported in the 1934 Land Acquisition Reports*[1]

Species	Tract 52			Tract 48[2]			Volume ranking of species in tabonuco forest.**
	Standing volume (m^3/ha)	Percent	Total volume (m^3)	Standing volume (m^3/ha)	Percent	Total volume (m^3)	
Dacryodes excelsa	4.681	90.4	952	3.358	51.9	535	1
Manilkara bidendata	0.029	0.6	5	0.903	14.0	144	10
Magnolia splendens	0.115	2.2	24	0.690	10.7	110	***
Sloanea berteriana	0.155	3.0	31	0.207	3.2	33	3
Ocotea portoncensis	*	*	*	0.201	3.1	32	*
Ocotea moschata	0.012	0.2	3	0.201	3.1	32	13***
Eugenia stahlii	0.006	0.1	1	0.127	2.0	20	8
Prestoea montana	0.029	0.6	5	0.121	1.9	19	2
Buchenavia capitata	0.006	0.1	1	0.121	1.9	17	7
Guarea ramiflora	0.017	0.3	4	0.069	1.1	11	20
Didimopanax morototoni	0.023	0.4	5	0.046	0.7	7	8
Znga fagifolia	0.046	0.9	9	0.029	0.4	5	16
Znga vera	*	*	*	0.029	0.4	5	17
Tabebuia heterophylla	*	*	*	0.017	0.3	3	15
Calycogonium squamulosum	*	*	*	0.012	0.2	2	14***
Alchorneopsis floribunda	0.006	0.1	1	0.012	0.2	2	22
Byrsonima spicata	*	*	*	0.006	0.1	1	*
Andira inermis	0.006	0.1	1	0.006	0.1	1	25
Trichila pallida	0.006	0.1	1	0.006	0.1	1	*
Cordia borinquensis	*	*	*	0.006	0.1	1	26
Pterocarpus officinalis	0.006	0.1	1	*	*	*	*
Zanthoxylum martinicensi	0.006	0.1	1	*	*	*	*
Other species	0.029	0.6	18	0.305	4.7	49	*
Total	5.18	100	1,063	6.47	100	1,031	...

*Not reported.

**Briscoe and Wadsworth 1970.

***Indicators of Colorado forest (Wadsworth 1970b).

[1]Includes all identified species having a diameter at breast height equal to or greater than 25 cm (10 inches). From Gerhart 1934a,b.

[2]Species are listed in order of abundance in tract 48.

in 1935, in an area to the northwest of the watersheds known as Coca Valley. Initially, Spanish cedar ***(Cedrela odorata)*** and moca ***(Andira inermis)*** ***were*** planted (Marrero 1947). However, both species failed within the year and complete replanting with mahogany ***(Swietenia macrophylla)*** and smaller amounts of Jacama ***(Pouteria multiflora)*** was done between 1936 and 1938. Of the total area replanted, 53 percent was considered "successful" in 1947 (Marrero 1947).

In 1938 a small plantation of mahogany, ausubo, and jacama was established in the northern section of tract 48 (table 7). This area was considered the "most successful plantation in the Luquillo Mountains and one of the best on the Island" (Marrero 1947). Seedling survival was unusually high, especially for ausubo and jacama, and no replanting was necessary. After 6 years, the mahogany had an average height of 10.6 m and diameter of 10 cm. The success of this plantation is considered to have been the result of a very good site and excellent care by a small crew of experienced workers.

Between 1936 and 1945, two plantations were established in tract 52 (table 8). Both of these plantations were located on the lower elevations of the Rio Mameyes Valley and outside the vicinity of the watersheds (Marrero 1947). The initial plantings of mahogany and moca failed as they did in most sections of the Luquillo forest. However, replantings of ausubo and mahogany were "promising" in 1947 (Marrero 1947).

In 1955 plantations of African ***(Khaya nyascia)*** and Honduran ***(Swietenia macrophylla)*** mahogany were planted in gaps and openings along the Bisley road from Commonwealth Rt. 988 to watershed 3 (Marrero 1957). Although survival was high after the first year, the overstory was opened to promote growth. Debris from wind breakage during the 1956 hurricane also eliminated some seedlings.

In 1957 U.S. Forest Service's Forest Management Plan designated the Bisley and surrounding areas as commercial timber land. The management plan proposed timber stand improvement, including vine removal and selective thinning. A 1965 revision of the 1957 Forest Management Plan classified the area as "least accessible" forest because most of the area was greater than 0.4 km from a paved road.

CONCLUSIONS

For nearly 440 years, from the discovery by Europeans to the purchase by the U.S. Forest Service, the resources of the Bisley watersheds have been used and the landscape transformed. Although the experimental drainages were never completely cleared or drastically altered, they have been selectively logged, fished, and probably explored for placer ores. In addition, the watersheds have experienced numerous natural disturbances such as hurricanes and flooding. Given the nature and relatively low frequency of human-induced disturbances, their impact was probably greater on the forest's structure than on its long-term productivity.

Table 7.—*History of planting in tracts 46 and 48*[1]

Species	No. trees planted per year or (kg of seed) planted per year					
	1936	1938	1939	1941	1942	Total
Andira inermis	(1,943)	...	...	...	...	(1,943)
Cedrela mexicana	130,000	...	...			130,000
Lucuma *multiflora*	...	...	(360)	:::	:::	(360)
Manilkara nitida	...	...	10,000	...	...	10,000
Swietenia macrophylla	...	80,000	65,000	...	...	145,000
Total trees planted	130,000	60,000	75,000	...	...	285,000
Total kg seeds planted	1,943	...	360	...	...	2,303

[1]Total area of plantation = 140 ha from Marrero 1947.

Table 8.—*History of planting in two plantations* at *lower elevations of the Mameyes River Valley in tract* 52[1]

Species	No. trees planted per year or (kg of seed) planted per year						
	1936	1938	1939	1941	1942	1945	Total
Albizzia lebbeck	...			1,200	...	...	1,200
Andira inermis	(2,219)	:::	:::	...	...	...	(2,219)
Byrsonima spicata	...	...	497	...			497
Cassia siamea	...	...	...	5,800	:::	:::	5,800
Casuarina *equisticolia*	...	...	...	...	5,000	...	5,000
Cordia alliodora	...	...	923	22,240	2,150	...	25,313
Eucalyptus robusta	...	...	...	1,140	...	...	1,400
Guarea trichilioides	...	...	299	...	...	2,400	2,699
Manilkara bidentata	...	...	5,000	...	...	...	5,000
Montezuma speciosissima	...	...	3,378	...	...		3,378
Swietenia candollei	...	...	22,000	8,300	8,700	:::	39,000
Swietenia mahagoni	130,972	10,000	...	...	...	...	140,972
Tabebuia heterophylla	...	...	...	...	...	3,400	3,400
Total trees planted	130,972	10,000	32,097	38,940	15,850	5,800	233,659
Total kg seeds	2,219	...	...	...	...	...	2,219

[1]Total area of plantations = 110 ha. From Marrero 1947.

The major obstacle to the exploitation of Bisley resources has been the inaccessibility of the region. High rainfall, highly dissected terrain, and slippery clay soils combine to make transportation in the area difficult. Agriculture, forestry, and mining operations have all been constrained by the difficulties of transporting goods to regional markets.

The most rapid change to the landscapes of the Bisley watersheds and the Luquillo Mountains occurred in the 19th century and the beginning of the 20th century. At this time, agricultural activity in the region was at a maximum; timber was being exported from the area, and cooper mines were active in the Rio Blanco area (fig. 11). In addition to human activity, several large hurricanes occurred during this period, specifically in 1892 and 1932. The impact of these storms on the relatively open landscape of the period was probably greater than it would have been on the pre-European or present landscape.

The temporal and spatial patterns of human-related disturbance contrast with the disturbance pattern associated with natural disasters. Before human intervention, hurricanes and tropical storm were the major cause of disturbance in the watersheds. Although tree throws, landslides, and floods associated with these storms act selectively on different parts of the landscape, these storms synchronously stress relatively large areas by similar intensities. In contrast, human-related disturbance affected different habitats at different times. Mining affected the stream channels of the Mamayes and Sabana Rivers. Logging and charcoal production preferentially removed particular species from ridge tops and valley walls. Agriculture opened up areas adjacent to the stream channel.

The net result of selectively disturbing different habitats at different times may be a reduction in the extent of uniformly developed stands left by the larger scale, storm-associated disturbances. Moreover, human interference has apparently increased the forest's spatial heterogenity. This alteration in the synchroneity of development is contrary to the effect of human disturbance in temperate forests of North America (Boreman and Likens 1981; Cronon 1983). In these compositionally uniform forests, widespread clear cutting has resulted in an appreciable increase in the area occupied by even age stands.

Furthermore, recent human intervention in many temperate forests has changed the magnitude and frequency of some natural disturbances, like fire. Human intervention in the Bisley forests has had no known effect on the frequency of disturbance induced by meterologic events. The significance of fence building and partitioning the landscape also appears to be less in the Bisley forest as compared to the temperate forests of New England (Cronon 1983).

The selective type of disturbance in the Bisley watersheds is also different from the traditional disturbance left by the slash and burn agriculture. In these cases small but continuous areas are disturbed by a synchronous event of uniform intensity. The net result is a patchwork of tracts in different stages of

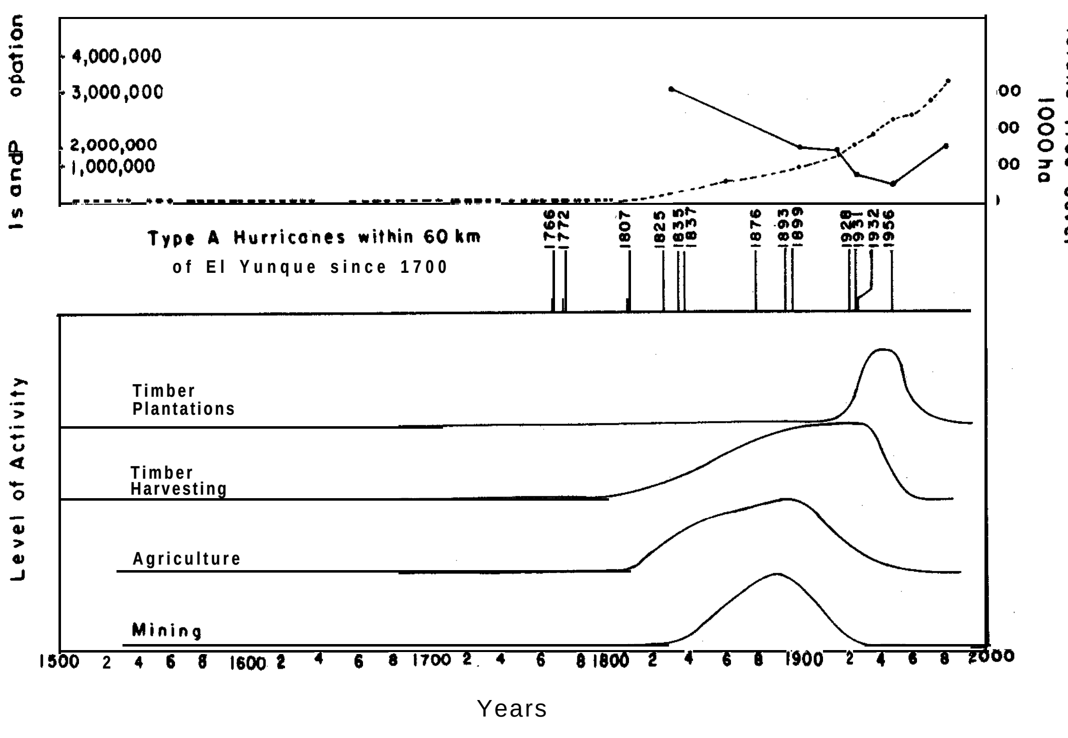

Figure IL-Schematic diagram of disturbance in the Bisley watershed area.

regeneration. Although this mosaic pattern can be seen in parts of the Luquillo Mountains, disturbance in the Bisley area left a heterogenous pattern rather than a patchwork mosaic.

Since their purchase in the mid-1930's, the experimental watershed areas have been relatively undisturbed and allowed to reforest. Areas adjacent to the watersheds that were altered to a greater degree were replanted with a variety of timber species. The success of these reforestation programs is a measure of the landscape's resiliency.

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Appendix

Chronology of land use in the Bisley experimental watersheds

1498—Columbus brought cane sugar to the New World and visited Puerto Rico.
1509—Cristobal de Guzman farm in the Rio Mameyes drainage had 50 slaves.
1513—Beginning of placer gold mining in Puerto Rico.
Spanish Crown granted titles to settlers with land holdings in excess of 68 ha (170 acres).
1530—The Luquillo mine and the farm of Cristobal de Guzman were burned and destroyed during a Carib Indian attack.
1533—Puerto Rico had 10 sugar mills that produced about 155 tonnes of sugar per year.
1582—Last Indians to light the Spanish had their stronghold in the Luquillo Mountains. Settlements in Sabana and the Espiritu Santo drainages were abandoned due to repeated attacks by Indians.
1774—Town of Farardo was founded.
1778—Royal charter issued by Spanish Crown granted ownership of occupied lands to inhabitants and set up governing board to oversee distribution of unoccupied public lands.
1815—Spanish Crown removed trade restrictions and openeded Puerto Rico to world trade.
1830—Land distribution programs began on the flanks of the Luquillo Mountains.
1839—Spanish Crown ordered the establishment of a board to protect forests, fish, and wildlife. Board recommended that no cutting be allowed along the margins or in the headwaters of rivers.
1857—Gregorio and Zoilo Boyley sold tract 48 to Juan Jose Boyley. The 400-acre tract was called "La Sierra" de Luquillo. Throughout the period the area was culled for ausubo *(Manilkara bidentata),* tabonuco *(Dacryodes excelsa),* and fuelwoods. Coffee, bananas, and subsistence crops were also planted on small farms and plantations in the region.
1860—First allocation of public money for forest management in Puerto Rico.
1880—Town of Rio Grande was founded.
1870-A French mining company made several placer excavations in the upper Mameyes River Valley.
1876—September 13, Hurricane San Felipe caused major flooding in eastern Puerto Rico.
1891—August 19, Hurricane San Magin caused major flooding in eastern Puerto Rico.
1893—Juan Jose Boyley sold tract 48 to Eduardo D. Gonzales.
1898—Crown lands of Puerto Rico passed from Spain to the United States.
1899—Hurricane caused major flooding on Rio Mameyes at Commonwealth Rt. 191 and destroyed coffee plantations in the Bisley area. Population densities in the foothills and coastal plains regions of the Luquillo Mountains were between 40 and 100 people/km^2.
1903—United States proclaimed the Luquillo Forest Reserve, which is now known as the Caribbean National Forest. At this time the Bisley area was privately owned and was not protected by the Crown lands or the original reserve. The entire mountainous portion of the Sabana Valley had been logged to some extent by this date.
1903—Requests for eight placer mining concessions in the Sabana area were filed with the Puerto Rican Department of Public Works. However, the claims were cancelled when the applicant failed to provide the necessary deposit. Throughout this period, placer prospecting occurred in the upper Mameyes valley and in the Rio Blanco area.
1918—Several houses were occupied in the Bisley area near the Rio Mameyes.
1918—August 22, Hurricane San Hipolito caused flooding in eastern Puerto Rico.
1920—First of two saw mills was established in the Sabana valley and was operational for 15 years.
1920's—Tracts 48 and 52 were culled for ausubo, tabonuco, and fuelwood.
1923—Saw mill was established in the Rio Espiritu Santo and was operational for 11 months.
1928—Hurricane caused major flooding on Rio Mameyes at Highway 191.
1931—Hurricane San Nicolas caused flooding in eastern Puerto Rico.
1932—Hurricane caused major flooding on Rio Mameyes at Highway 191.
U.S. Forest Service records state that tract 48 was "severely damaged" along the boundary with the National Forest (Gerhart 1934a).
1934—Land acquisition reports for tracts 48 and 52 were prepared by Gerhart (1934a,b) of the U.S. Forest Service.

1935—Tract 48 and the **Coco** valley area near Rio Mameyes were planted with Spanish Cedar *(Cedrela odorata)* and **moca** *(Andira inermis).* Both species failed. Complete replanting with mahogany *(Swietenia mahagoni)* was done between 1936 and 1938.

1936—Tract 52 was sold to U.S. Forest Service. Acquisition report states that erosion on the tract was "of slight consequence." However, the northern portion of the tract had been "exploited recklessly" (Gerhart 1934b).

1937—Second of two saw mills was established in the Sabana valley. Two million board feet of tabonuco were removed from the Sabana and **Mamayes** valleys.

1936-1941—The U.S. Forest Service's La Perla project developed plantations in the Rio Mameyes and Rio Sa **bana** drainages.

1938-A small, mixed species plantation of 28 ha was established in tract 48. A U.S. Forest Service report states that the plantation was "unquestionably the most successful plantation of Luquillo and one of the best on the island. This is probably the only case in the island where replanting has not been necessary' (Marrero 1947).

1940's—Sections of the Bisley area to the west of the watersheds were logged. Logs were transported by oxen to the road head past watershed 3. Civilian Conservation Corps workers camped across the road between watersheds 2 and 3. A small supply store was established at the road bend between these watersheds.

1940's—Charcoal production was the forest's largest forest industry. About 3.6 million dollars worth of charcoal was removed from the Luquillo Mountains each year.

1950—Trend of natural reforestation began in Puerto Rico.

1955—U.S. Forest Service established mahogany plantations in Bisley area. Both *African (Khaya nyascia)* and Honduran *(Swietenia macrophylla)* were planted in gaps and openings along the road from Commonwealth Rt. 988 to watershed 3.

1956—Hurricane caused breakage of branches, which eliminated some of the seedlings in the **Bisley/Sabana** mahogany plantations. Plantations at Catalina also suffered wind damage, mostly in the form of breakage.

1960—Major flooding occurred in Rio Mameyes at Highway 191.

1969—Major flooding occurred in Rio Mameyes at Highway 191.

1970—Major flooding occurred in Rio Mameyes at Highway 191.

1972—Major flooding occurred in Rio Mameyes at Highway 191.

1979—Hurricanes David and Frederick caused flooding and landslides in eastern Puerto Rico.

1980's—Local resident claimed a daily catch of over 4.6 kg (10 lb) of fresh water shrimp from the tributaries of the Rio Mameyes adjacent to the Bisley watersheds.

1985—U.S. Congress authorized watershed research at the Institute of Tropical Forestry, and the Bisley area was selected for detailed studies.

Scatena, Frederick N. 1989. An introduction to the physiography and history of the Bisley experimental watersheds in the Luquillo Mountains of Puerto Rico. Gen. Tech. Rep. SO-72. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 22p.

Paper summarizes the physiographic setting and historical uses of the Bisley experimental watersheds in the Luquillo Experimental Forest to provide background information for ecological and silvicultural research studies initiated by the Institute of Tropical Forestry.